A Computational Study to Determine the Critical Velocity Required to Initiate Explosively Loaded Munitions

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Abstract

When a fragment (projectile) impacts a stack of munitions, a strong shock can be produced which can initiate/detonate the explosive in the munitions. The critical velocity required to initiate the explosive is principally a function of the diameter of the fragment. However, the shape of its tip also influences the initiation process. A computational study was conducted to aid in understanding these effects and to determine the critical velocities of projectiles. This understanding is important in preventing munitions explosions.

The munitions were simulated as explosives with different types of covers, and fragments were simulated as projectiles of different shapes and sizes. Two-dimensional (2-D) simulations of projectile impact on covered explosives were made. The response of the munitions was measured by monitoring pressure at various locations inside the explosive layer.

Computational results show that for large (more than 5-mm) diameter projectiles, higher critical velocities than predicted by a well-known model (Jacobs-Roslund) are required to initiate the explosive. But for small diameter projectiles, the velocities calculated using the CTH code and the velocities predicted by Jacobs-Roslund are close.

Introduction

When a projectile impacts a munition, the loading produced in the explosive may initiate reaction. The critical velocity required to cause reaction is principally a function of the projectile's diameter. But the casing thickness of the munition also plays a significant role in preventing the reaction in the munitions. The response of high explosives to projectile impact is of considerable importance in assessing the vulnerability of munitions. Their response, when impacted by small but high-speed projectiles, is of particular interest.

Conditions required for shock-to-detonation transition following the impact of projectiles having larger diameters have been well characterized and are described by an empirical relationship commonly known as the Jacobs-Roslund equation. The equation was developed to aid in resolving the conflicting data in the literature and to predict the response of munition explosives for various conditions of fragment or projectile impact. The equation determines the critical velocity of the fragment or projectile. The critical velocity is defined as the minimum velocity of the projectile, which causes the explosive to detonate.

The shock magnitude and duration are very important in controlling buildup to detonation. Once the explosive has been initiated, the detonation wave will continue to propagate throughout the explosive as long as the diameter of the initiated explosive is sufficient. If this region is too small to sustain the detonation, rarefaction will influence the propagation of detonation and restrict the reaction. This suggests that projectile diameter and impact velocity are the main parameters that control the initiation process. A projectile with a larger diameter produces a broader shock wave that is less susceptible to rarefaction and, therefore, more effective in initiating the explosive.

In order to understand the response of munitions impacted by various types of projectiles, a computational study using the CTH code was conducted. The History Variable Reactive Burn (HVRB) model was used. Predictions of projectile-impact initiation were much better with the HVRB model than some other models.

The work described here is a small part of a larger project to determine initiation algorithms suitable for inclusion in the codes. Such algorithms should be simple, because they are used many times during the course of a vulnerability analysis. The overall ARL program combines experimental and computational work, and results of the larger program will be reported elsewhere. In this paper, some of the computational results will be reported, and we also report how these results compare to predictions made with the Jacobs-Roslund equation, a very simple for predicting threshold velocities for the initiation and detonation of the explosives.

Description of CTH and the HRVB Model

CTH was developed by the Sandia National Laboratories. It is intended to provide capabilities for modeling dynamics of multidimensional systems with multiple materials, large deformations, and strong shock waves. The code uses finite difference analogs of the Lagrangian equations of momentum and energy conservation with continuous rezoning to construct Eulerian differencing. Shock and detonation waves are treated using the method of artificial viscosity. CTH uses analytical (Mie-Gruneisen, JWL, etc.) and tabular (Sesame) equations of state, as well as modern constitutive models (Johnson-Cook; Zerilli-Armstrong) including fracture (void insertion). Three reactive and two porosity models are also incorporated into the code.

These models provide an opportunity to treat complex material behavior, including melting, vaporization, solid-phase transitions, chemical reaction, and electronic excitation and ionization. The reaction model is the Programmed Burn model for detonation propagation and the HRVB model for shock initiation. The Programmed Burn model forces detonation at the characteristic propagation velocity through a specified portion of the computational mesh. The HVRB model (Kerley 1992) is designed to treat the process of initiation of detonation in shock-loaded high explosives.

The March 1999 release of CTH was used during the course of this study, because it offered more versatile problem configuration options, more realistic constitutive models, and a more accurate reactive model than earlier versions of the code.

SIMULATION CONFIGURATIONS

The projectile/target configuration was varied in various computations. Various types of projectiles were simulated during the course of this study. Variations included shape (spheres and cylindrical with hemispherical tip), length (2.54 cm to 10 cm), diameter (5-mm to 15-mm), and velocity (1.00 km/s to 4.50 km/s). All projectiles impacted with zero-degree obliquity to the upper surface of the target.

The munitions (targets) were represented as explosive cylinders with covers of varying thickness (1.25 mm to 15.0 mm). The target was simulated as a cylinder of varying depth and diameter. The explosive used in most of the computations was a 30-mm-deep and 60-mm-diameter Composition B (Comp B) charge but in some other computations, the size of the explosive was varied.

Two-dimensional (2-D) plane strain computations of projectile impact on these targets were made. The 2-D simulations afforded considerable savings in running and turn around time. Thus, they allowed a greater number of computations with variations in the projectile and target geometries. The projectile, often referred to as a rod, is always characterized by its diameter, and it may be either sphere or cylinder with hemispherical tip. Square 0.1-mm zones were used in two-dimensional computations.

Some computations were also performed using 0.2-mm and 0.4-mm square zones, and results were compared with the computational results from 0.1-mm square zones. The 0.2-mm and 0.4-mm square zone simulations were performed in anticipation of transitioning from 2-D to 3-D simulations.

The response was measured by monitoring the pressure at various locations inside the explosive layer. The reaction of the explosive was also monitored at various times and locations. Many configurations were simulated. One of the configurations is shown in Figure 1. The figure shows a projectile, cover and explosive.
Some of the computational configurations are summarized in Table 1.

Table 1. Computational Configurations

Cover (H, mm)	Diameter of Projectile (D, mm)	H/D
1.25	5.00	0.25
2.50	5.00	0.50
5.00	5.00	1.00
2.25	10.00	0.225
5.00	10.00	0.50
10.00	10.00	1.00
3.75	15.00	0.25
7.50	15.00	0.50
15.00	15.00	1.00

Initiation of Composition B by Projectile Impact

General

Projectile-impact simulations were run in order to determine critical velocity for initiation as a function of projectile diameter and cover plate thickness.

Reaction variable and pressure contour plots were made. Plotting contours of reaction variable at various times facilitated visualization of the results. Detonation was identified as a region of closely spaced contours of both variables. Pressure histories at Lagrangian stations in the explosive were also useful.

Axisymmetric computations were made for some of the configurations. The projectile's diameter was varied between 5.0 mm and 15.0 mm, and cover thickness was varied between 1.25 mm and 15.0 mm. The ratio of projectile diameter and cover thickness was kept the same for both sets of configurations (spherical and cylindrical projectiles).

Spherical Projectiles

Spherical projectiles of different diameters and velocities impacted 30.0-mm-deep and 60.0-mm-diameter Composition B charge with covers of various thicknesses.

For a 5.0-mm-thick cover and a 10.0-mm diameter projectile the explosive detonated when the impact velocity was 3.2 mm/µs but did not detonate when the impact velocity was decreased to 3.1 mm/µs.

Figure 2 shows a sequence of reaction variable and pressure contour plots for initiation of Comp B target by the impact of a 5-mm-diameter spherical projectile at 3.2 mm/µs. Comp B detonated at about 3 µs. The explosive detonated close to the cover. When the rod velocity was decreased to 3.1 mm/µs or less, the explosive did not detonate. A sequence of reaction variable and pressure contour plots for nondetonating Comp B is shown in Figure 3. The contours are separated and do not converge, even 20 µs after impact. Although the explosive did not detonate when the projectile hit the charge at a velocity of 3.1 mm/µs, it did produce some reaction in the explosive.

Cylindrical Projectiles

In this set of computations, cylindrical projectiles with hemispherical noses were used. The diameters, lengths, and velocities of the rod varied in various computations. These cylindrical projectiles impacted a 30-mm-deep and 60-mm-diameter charge that had a cover of various thickness.

Figure 4 shows a sequence of reaction variable and pressure contour plots for initiation of Comp B target by the impact of a 15-mm-diameter cylindrical with hemispherical-nosed projectile at
3.7 mm/μs. The charge had a 15.0-mm thick cover. The reaction variable contours remained spread out for a long period of time. The penetrator penetrated about 5 mm into the explosive before the reaction started. At about 7 μs, the reaction variable contours became closely spaced near the axis, indicating that build up to detonation had occurred. The detonation then propagated away from the penetrator and into the remainder of the charge.

More simulations were run using various impact velocities. When the velocity of the projectile was decreased to 3.6-mm/μs or lower, the explosive did not detonate. A sequence of reaction variable and pressure contour plots for nondetonating charge were made and are shown in Figure 5. The contours were separated and did not converge, even 20 μs after the impact. Although the explosive did not detonate when impact velocity of 3.6-mm/μs was used, it did produce some reaction in the explosive.

As mentioned earlier the diameter of the projectile and cover thickness were varied in various computations. A product of velocity and diameter of the projectile ($VD^{0.5}$) as a function of H/D is plotted in Figure 6. In the J-R equation, ($VD^{0.5}$) depends only on the ratio H/D. This figure shows that for smaller diameters the computed and predicted velocities are very close but for larger diameter they deviate. The velocities considered here are higher than those normally considered with J-R. These results show that J-R underestimates the diameter dependence at these velocities.

A comparison of the computed velocity and velocity calculated by using Jacobs-Roslund relationship for various configurations is shown in Table 2. This table shows that for large (more than 5-mm) diameter projectiles, higher velocities than predicted by Jacobs-Roslund are required to initiate the explosive. But for small diameter projectiles, the velocities calculated using the CTH code

Table 2. Comparison of Calculated and Predicted Velocities

Cover (H [mm])	Diameter of Projectile (D [mm])	H/D	Velocity ($mm/\mu s$)		Zone Siz
			CTH	J-R	mm
1.25	5.00	0.25	3.35	2.98	0.1
2.50	5.00	0.50	3.75	3.35	0.1
5.00	5.00	1.00	4.25	4.08	0.1
2.25	10.00	0.225	2.75	2.08	0.1
5.00	10.00	0.50	3.15	2.37	0.1
10.00	10.00	1.00	4.35	2.89	0.1
3.75	15.00	0.25	2.45	1.72	0.1
7.50	15.00	0.50	2.85	1.93	0.1
15.00	15.00	1.00	3.65	2.36	0.1
4.763	25.40	0.1875	2.10	1.28	0.1
4.763	25.40	0.1875	2.10	1.28	0.2
4.763	25.40	0.1875	2.10	1.28	0.4
1.25	5.00	0.25	3.35	2.98	0.1
1.25	5.00	0.25	3.35	2.98	0.4

and the velocities predicted by Jacobs-Roslund are close. Table also shows that changing the zone size from 0.1-mm to 0.4-mm does not have any effect on the critical velocity of the projectile. The results suggest that the Jacobs-Roslund criterion may be valid for small diameter projectiles but may not be valid for large diameter projectiles, and perhaps, 2-D simulations may be less accurate as compared to 3-D simulations. Some of the results compared, here, are extrapolated beyond the prediction capability of Jacobs-Roslund equation and, obviously, those predicted velocities would not match with the computed velocities.

Discussion and Summary

A computational study was conducted to determine the critical velocity of the projectile. The History Variable Reactive Burn (HVRB) model, simulating projectile-impact initiation, was used. The munitions were simulated as explosive cylinders with cover of varying thickness. The fragments were simulated as projectiles of different shapes and sizes.

Two-dimensional simulations of projectile impact on covered explosives were made. The computational results did not match closely with the prediction of Jacobs-Roslund. In future, some of the computations will be done using 3-D code. The zone size of 0.1-mm was used in the 2-D computations. Using the same zone size, in 3-D computations would make the problem much bigger and would take a lot of time to run. To determine an appropriate zone size, 2-D computations were done using 0.1-mm, 0.2-mm and 0.4-mm cell sizes. The comparison of the computational results show that the pressures and critical velocities for these sizes were about the same. This means that the zone size larger than 0.1-mm can be used, in 3-D computations.

Two types of projectiles (spherical and cylindrical) were used in the computational study. The computed critical velocities, of the spherical and cylindrical projectiles, to detonate the explosive were about the same.

A relationship between the critical velocity of the projectile and thickness of the cover was established. It showed that higher velocity was required to detonate the explosive with thick cover. A relationship between the critical velocity of projectile and its diameter was also established. The results suggest that thinner diameter projectile required higher velocity and thicker diameter projectile required a lower velocity to detonate the explosive. These observations are well known to the explosive community. The calculations suggest that J-R may predict the proper trend with respect to H/D, but they may suggest that the JR diameter dependence is wrong at these relatively high velocities.

The computations were performed at zero degree obliquity. Future computations will be performed by varying the angle of attack between 0 and 90 degrees. The material and the nose shape of the projectile may also be varied.

Acknowledgements

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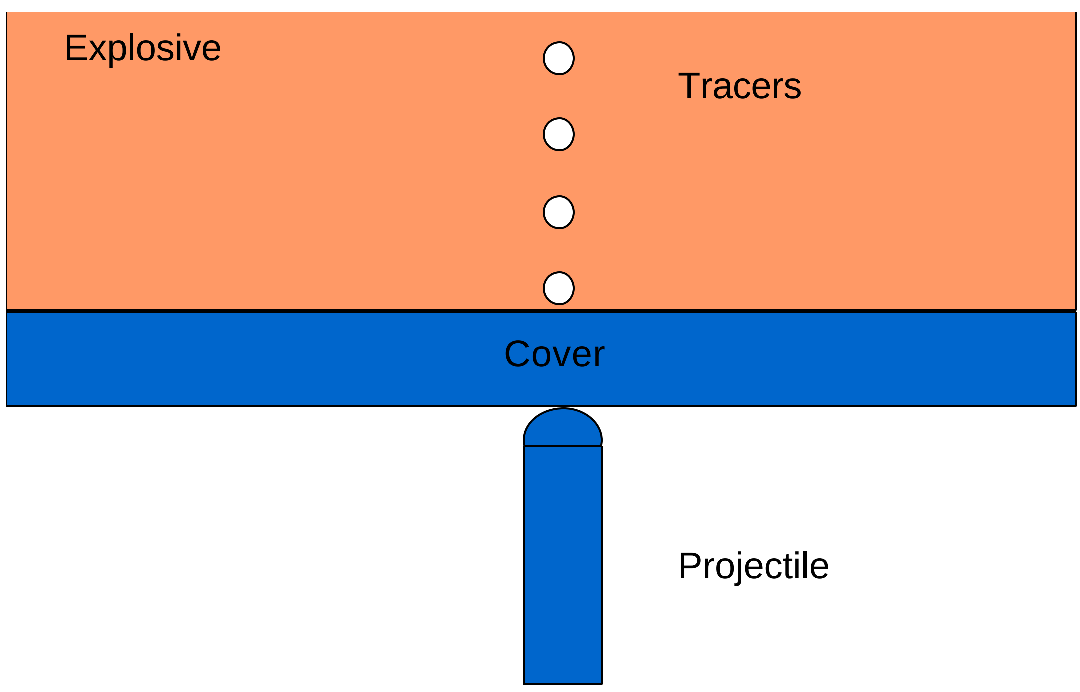


Figure 1. Projectile impacting the target

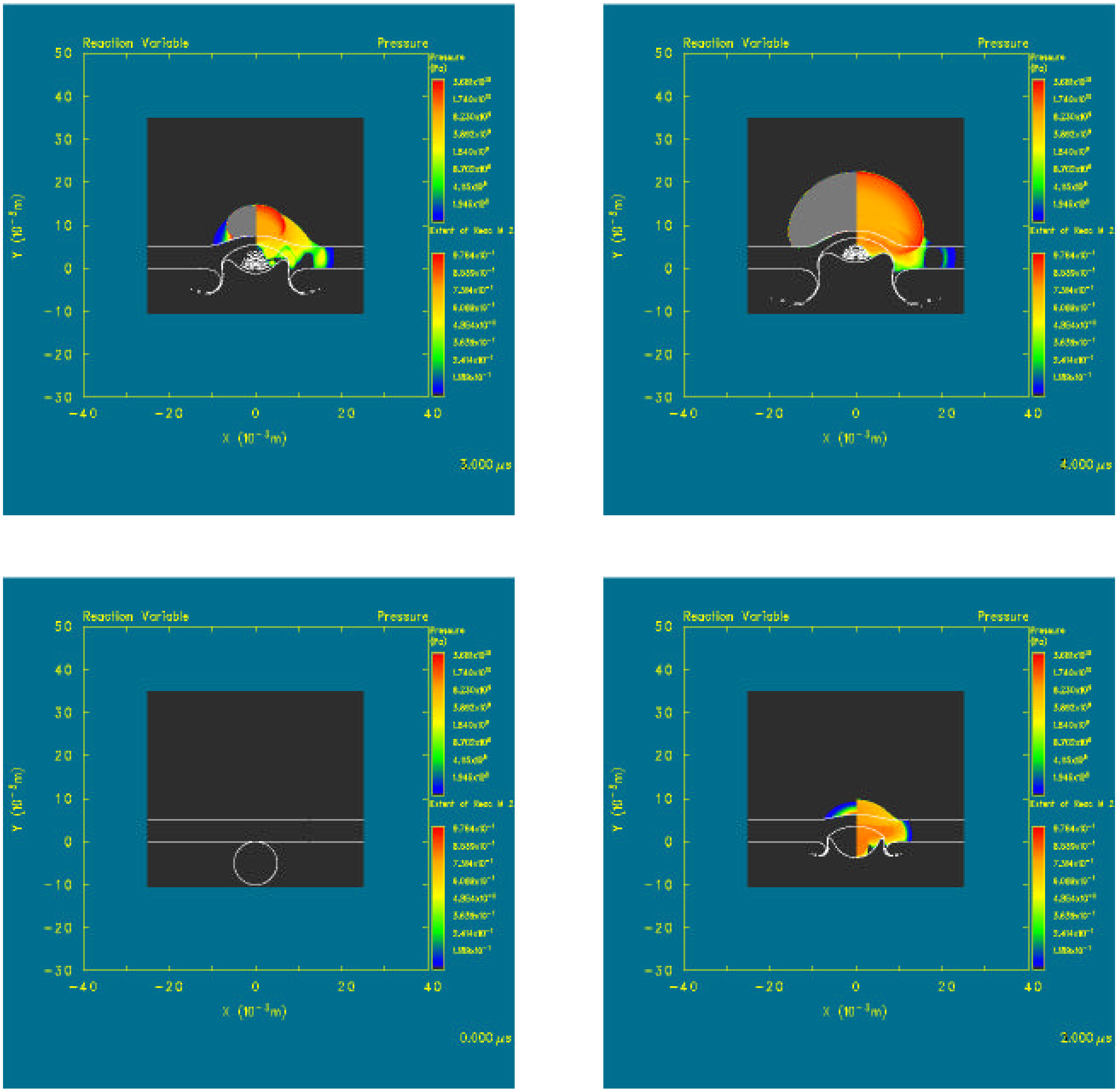


Figure 2. Pressure and Reaction Variable Contour Plots for the 3.2-mm/μ s Impact of a 5-mm Spherical Projectile Against Comp B with 5-mm Cover.

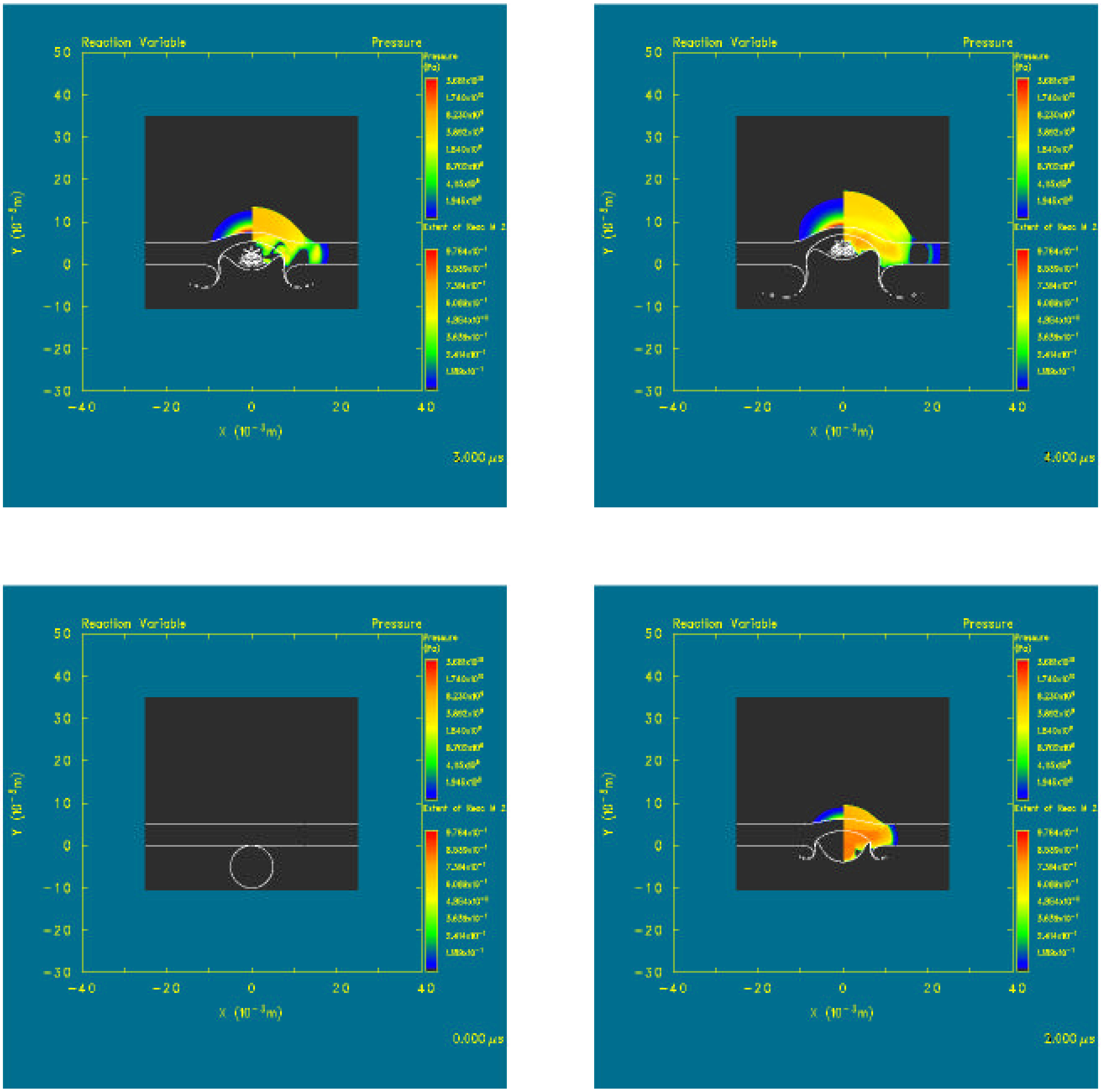


Figure 3. Pressure and Reaction Variable Contour Plots for the 3.1mm/ μs Impact of a 5-mm Spherical Projectile Against Comp B with 5-mm Cover.

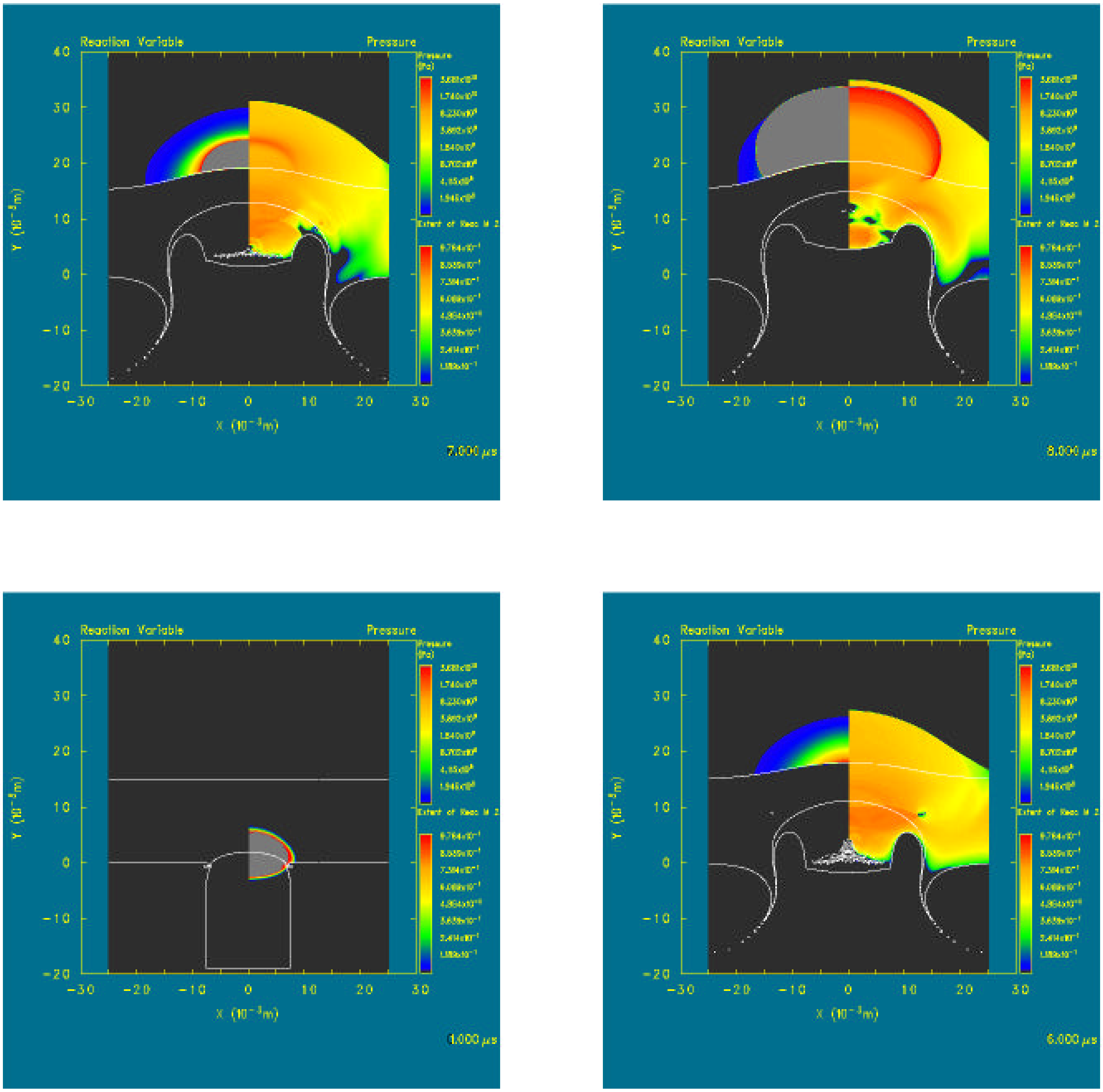


Figure 4. Pressure and Reaction Variable Contour Plots for the 3.7-mm/µs Impact of a 15-mm Cylindrical Projectile Against Comp B with 15-mm Cover.

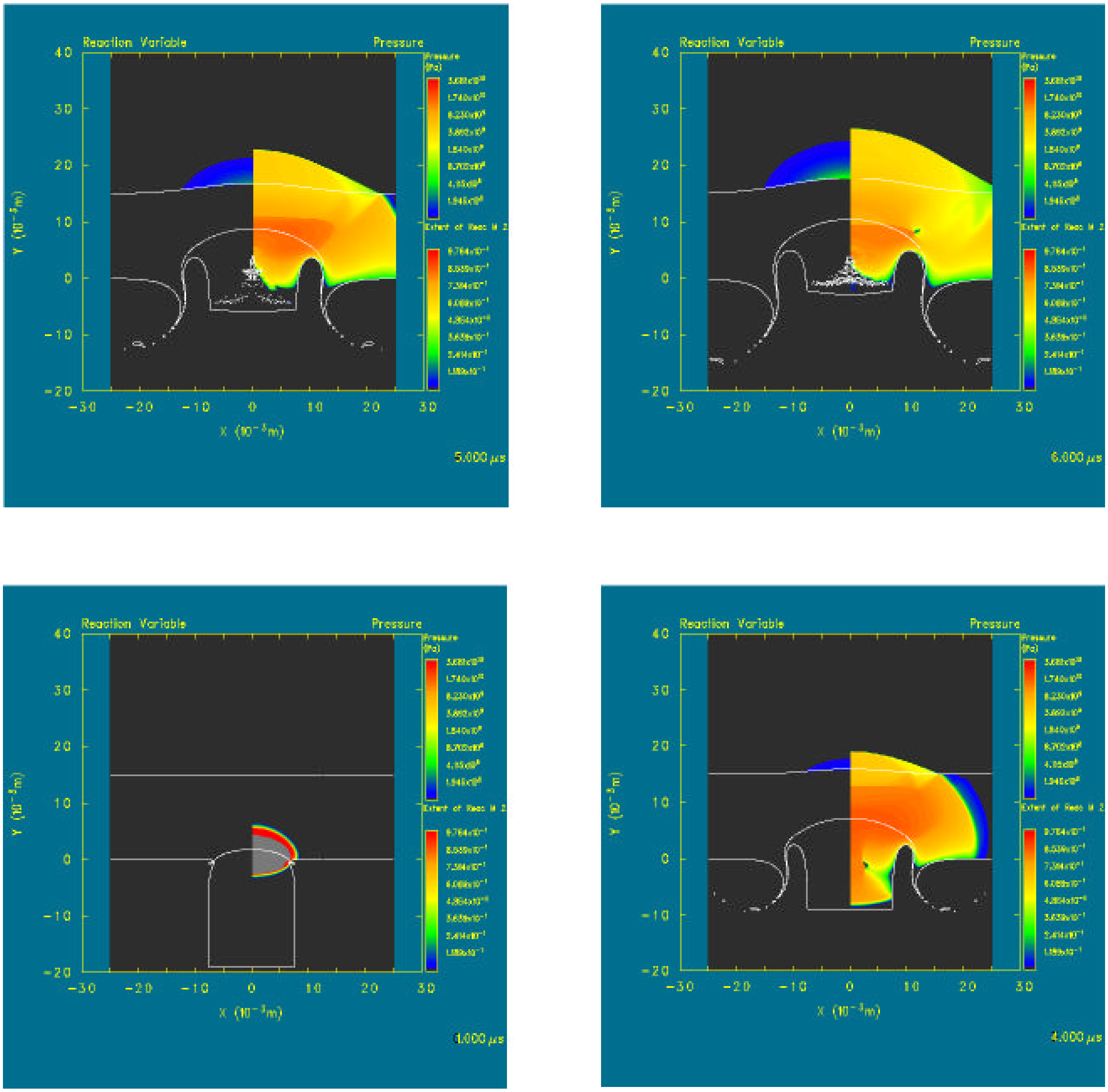
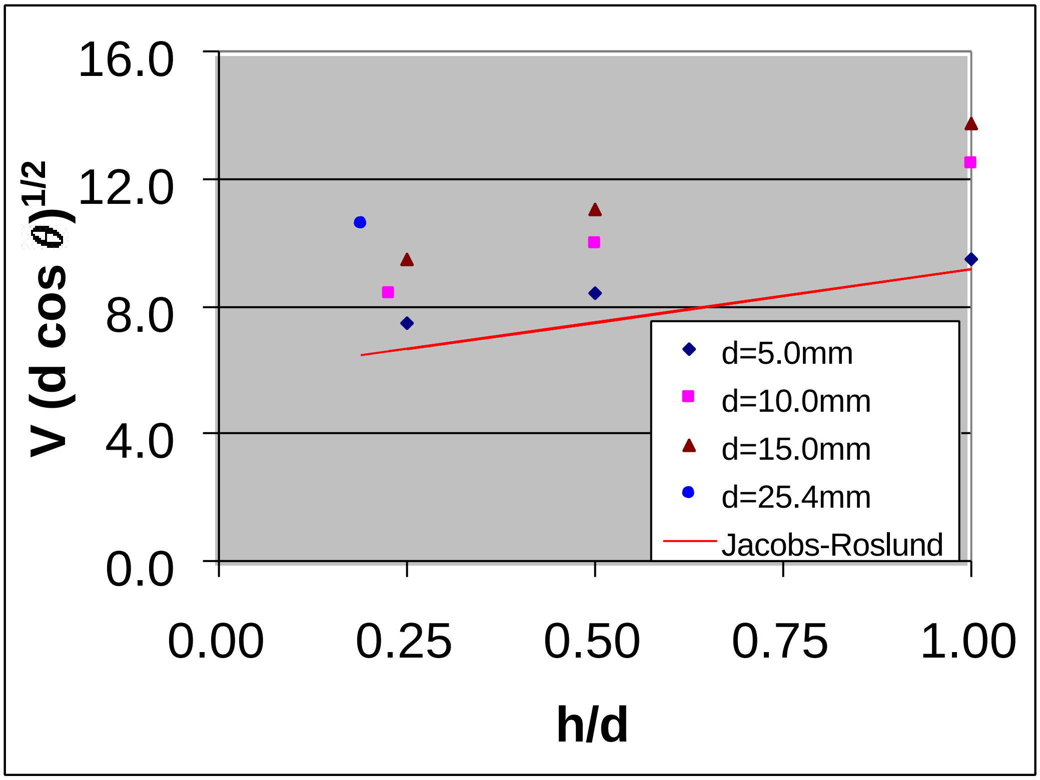


Figure 5. Pressure and Reaction Variable Contour Plots for the 3.6-mm/µs Impact of a 15-mm Cylindrical Projectile Against Comp B with 15-mm Cover.



16.0
12.0
8.0
4.0
0.0
0.00
0.25
0.50
0.75
1.00
h/d
V (d cos θ)^1/2
d=5.0mm
d=10.0mm
d=15.0mm
d=25.4mm
Jacobs-Roslund

Figure 6. Comparison of Computed and Predicted (J-R) Critical Velocties.